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FINAL REPORT

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AIRBORNE ASTRONOMY WITH A 150 μm - 400 μm HETERODYNE SPECTROMETER

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A. L. Betz, Principal Investigator

Center for Astrophysics & Space Astronomy,
University of Colorado, Boulder, CO 80309

ABSTRACT

This report summarizes work done under NASA Grant NAG2-753 awarded to the University of Colorado. The project goal was to build a far-infrared heterodyne spectrometer for NASA's Kuiper Airborne Observatory, and to use this instrument to observe atomic and molecular spectral lines from the interstellar medium. This goal was successfully achieved. Detections of particular note have been the 370 μm line of neutral atomic carbon, the 158 μm transition of ionized carbon, many of the high-J rotational lines of ^{12}CO and ^{13}CO between J=9-8 and J=22-21, the 119 μm and 163 μm rotational lines of OH, the 219 μm ground-state rotational line of H_2D^+, and the 63 μm fine structure line of neutral atomic oxygen. All of these lines were observed at spectral resolutions exceeding 1 part in 10^6, thereby allowing accurate line shapes and Doppler velocities to be measured.

I. Technical Overview

The following synopsis relies on the detailed presentations available from cited publications included here as Appendices. A list of corresponding publications is included on page 13. References to individual entries are noted in the text by a number in brackets (e.g., [1]). The text below begins with a technical review of the spectrometer and then details the specific astronomical observations accomplished with this instrument.

Our FIR heterodyne spectrometer has the 4 basic subsystems characteristic of most heterodyne instruments: a local oscillator (LO), a mixer, an intermediate-frequency (IF) amplifier, and a multi-channel radio-frequency signal analyzer (either a filter bank or an acousto-optic spectrometer: AOS).

The LO is an optically-pumped laser, and the mixer is a cooled Schottky-diode in a special corner-reflector mount. These components, together with the IF amplifier, are the critical "front-end" components of the spectrometer, and they are the only ones actually mounted on the telescope. The "back-end" components such as the filter bank are mounted in the experimenters' rack. They are non-critical in that they affect the resolution but not the sensitivity of the spectrometer. For this reason, a heterodyne

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spectrometer has a very practical advantage over an incoherent instrument for high resolution spectroscopy. A heterodyne spectrometer does its spectral analysis *after* "detection" whereas a spectrometer using incoherent detection does its resolving *before* detection. In this latter case, the inevitable losses and extraneous emissions of the spectrometer reduce the signal-to-noise ratio from that obtainable with a perfect instrument. On the other hand, the coherent (heterodyne) spectrometer does have an additional but fundamental source of noise from quantum fluctuations. Realistically however, the quantum-noise level of a heterodyne receiver even at $\lambda = 100\,\mu m$ is only $T_Q = 140$ K, or about 10^{-21} W Hz$^{-1/2}$, and thus is negligible compared to the non-fundamental noise of current receivers. Perhaps the most obvious advantage of heterodyne spectroscopy is its capability for ultra-high resolution. A velocity resolution <1 km/s can easily be achieved with a velocity-scale accuracy limited only by the knowledge of the laser and source line-frequencies.

The front-end components of our airborne spectrometer weigh 200 lbs. and have a moment of 800 ft-lbs. measured from the center of the air bearing on the KAO. The size of the laser-frame dictates the overall size of the front-end hardware. The frame is 40" L x 13.5" W x 8" H and consists of four 1-inch O.D. invar rods that separate 2 insulating granite end-plates. A 40" x 13.5" aluminum plate is attached to the top of the laser frame, and on it are positioned all the optical components of the spectrometer. The entire assembly fits halfway into the instrument cavity at the Nasmyth focus position. The other half of the spectrometer protrudes beyond the position of the standard instrument flange, but is braced to the instrument cavity. The standard instrument-mounting flange is removed, of course. More details of the instrument along with additional references may be found in the Proceedings of the 1994 Airborne Astronomy Symposium [3].

II. Scientific Program

FY91 Results

During FY91 the spectrometer was flown in four flight series: 1 G.I. flight in February, 1991 and 1 5-hr flight for us, 3 flights in March 1991 in NZ, 2 flights and 1 G.I. flight in August 1991, and 3 G.I. flights in Oct. 91.

(A) Detection of the H_2D^+ fundamental at 1370 GHz

The molecular ion H_3^+ is perhaps the most critical component in ion-molecule theories of interstellar chemistry. Its pivotal role is to initiate the formation of most molecular ions which in turn produce the more complicated neutral species. Unfortunately the observation of H_3^+ is hampered in dense molecular clouds because the ion has no permanent dipole moment and hence no allowed dipole transitions. The deuterated variant, H_2D^+, however, does have a moment of 0.6 D and permitted transitions. H_2D^+ also has a special chemical significance, because it is thought to be the source of the enhanced deuterium fractionation of molecules seen in cold clouds.

In Dec., 1990, and February, 1991, we searched for the $1_{01} - 0_{00}$ rotational transition of H_2D^+ at 1370 GHz (219 μm) in several galactic molecular clouds. Since this para-species transition is linked to the ground state, H_2D^+ could be detected in absorption against strong continuum sources as well as in emission from gas with densities near the

$\sim 2 \times 10^8\ cm^{-3}$ required to thermalize the J=1 rotational level. H_2D^+ could exist in such dense regions, as its formation is thought to be a product of cosmic ray ionization of molecular hydrogen followed by a proton exchange reaction.

The results on M42/IRc2 are shown in Figure 1 of Appendix A, which is a reprint of the Ap. J. (Letters) publication [1]. The absorption line is a 7-σ detection, centered at a V_{LSR} of $3.8 \pm 1.3\ km\ s^{-1}$. If we interpret it as the 1370 GHz $1_{01} - 0_{00}$ transition of para-H_2D^+, then the velocity is close to the 5 $km\ s^{-1}$ V_{LSR} of the "hot core" source near and in front of IRc2. The linewidth (FWHM) of $17 \pm 3.5\ km\ s^{-1}$ is also similar to the 10-$15\ km\ s^{-1}$ values noted for the "hot core". We have already seen OH at $119\ \mu m$ in absorption against the continuum of IRc2 at a similar velocity.

From the measured linewidth and the line center optical depth of 0.19, we calculate the column density of ground-state H_2D^+ to be $2.3 \times 10^{13}\ cm^{-2}$. This relatively large column density compared to the expected abundance of $H_3{}^+$, given the cosmic D/H ratio, suggests significant enhancement of H_2D^+. Since chemical fractionation processes for deuterium enhancement in molecules are effective only in cold (T < 30 K) gas, it may be that H_2D^+ results from cold mantle material ablated from grains by the hot wind from IRc2. Such an argument has been put forward by other observers to explain the high abundance of deuterated molecules in the IRc2 "hot core".

We also searched unsuccessfully for H_2D^+ in NGC 2264, a comparatively cold source for which Phillips and coworkers in 1985 reported the detection of a weak line at 372 GHz, the frequency of the lowest ortho-species transition of H_2D^+. Subsequently, more sensitive observations of the 372 GHz transition by van Dishoeck and coworkers in 1992 from the CSO and Pagani, Wannier, and Frerking in 1992 from the KAO have failed to confirm the initial tentative detection of the 372 GHz line. Consequently, our detection of a 1370 GHz absorption line in M42/IRc2 is now the only viable candidate for H_2D^+ in the interstellar medium. Given the difficulty of detecting the higher excitation 372 GHz line (because proton exchange likely keeps the ortho- and para-species energetically coupled), the next best way of "confirming" our line is to look for similar absorptions in the spectra of other strong continuum sources embedded in dense molecular clouds.

(B) Search for the H_3O^+ Fundamental at 984 GHz

A search for the 984 GHz transition of the hydronium ion, H_3O^+, was finally completed in a carry-over flight in Dec., 1990. The Orion/IRc2 region and W3 were the principal sources observed. Emission from the IRc2 region had earlier been reported from the lowest lying para-state transition at 307 GHz and more recently from the next highest para-transition at 364 GHz. In our observations no emission from the ortho-state fundamental at 984 GHz was detected, with an upper limit to the integrated intensity of $\sim 1 \times 10^{-5}\ ergs\ cm^{-2}\ s^{-1}\ sr^{-1}$ (assuming a $10\ km\ s^{-1}$ linewidth as seen in the other transitions). Considering the fact that the H_3O^+ line is near a strong atmospheric water vapor line, this is a good limit for a line at 984 GHz with state-of-the-art receiver noise temperatures of 8000 K (SSB). The significance of our non-detection is now being evaluated in light of some very recent measurements on the spatial distribution of the higher excitation lines done by Caltech investigators at the CSO. Although the non-detection of the 984 GHz line might help constrain the density in the H_3O^+ line formation region, any limit must be relaxed because of the uncertain effects of beam dilution for this particular

transition. As a guide, recent observations of the 307 GHz and 364 GHz lines show that the emission is confined to a ~20″region, whereas the KAO beam at 984 GHz is closer to 80″(FWHM).

(C) CO J=9-8 Line Radiation in Southern Sources

In March, 1991, we participated in the Southern Skies Expedition of the Kuiper Observatory to Christchurch, New Zealand. The primary goal of our flight program was to observe the J=9-8 rotational line of ^{12}CO and ^{13}CO in the Large Magellanic Cloud and selected high density molecular clouds observable only from the Southern Hemisphere. The high spectral resolution of our infrared heterodyne spectrometer is comparable to that of the millimeter-wave line receivers, which allows us to make specific comparisons with lower-J CO line profiles.

The LMC is known to have a low metallicity relative to the galaxy, and therefore the ultraviolet flux from newly formed stars can penetrate far deeper before being attenuated by dust than is the case in our own galaxy. The previously observed low intensity of CO radiation from the LMC has been attributed both to the relatively lower abundance of C and O, and also to the enhanced photodestruction of this molecule by UV radiation. Our upper limit to the J=9-8 intensity in N159 in the LMC shows that the beamfilling factor of dense molecular gas is much less than that in equivalent clouds in our own galaxy, consistent with this scenario. The J=9-8 CO observations of the LMC were analyzed and published with the C II work from the previous year.

Our observations of the J=9-8 lines of ^{12}CO and ^{13}CO were more fruitful in the dense clouds G333.6-0.2, RCW 57, M42, and NGC 2024. We find the ^{12}CO line to be significantly optically thick in all the detected sources. In G333.6-0.2 it's at least a τ of 10, if the $^{12}C/^{13}C$ isotopic ratio is ≥ 30. A similar result was seen previously in the Northern Hemisphere sources W3, M17, DR 21, and W51. Note that only a modest detection of the ^{13}CO line is needed to establish the ^{12}CO optical depth. The ^{13}CO J=9-8 line is more difficult to detect than some of the higher-J ^{13}CO lines, because it falls in the wing of a strong atmospheric water line where the transmission is at best only 50%.

The relatively high ^{12}CO optical depth may seem somewhat surprising, given the relatively low line intensities that were observed: $T_A^* \sim 10–20$ K. The gas must be either cold, significantly clumped, or more likely both. A full analysis of the Southern CO data is now in progress in concert with subsequent observations of higher J. The main import seems evident already: when averaged over our 1.4′ beam, much of the emission in the J=9-8 transitions of ^{12}CO and ^{13}CO appears to originate in the dense regions of the clouds with the same moderate excitation temperatures ($T_{ex} \sim 50$ K) seen in the low-J transitions. Although the J=9-8 data suggest that up to ~20% of the observed emission may originate in hotter material, there is no strong evidence for large scale distributions of hot gas (T>200 K) from observations of CO lines at wavelengths > 280 μm. This conclusion is at variance with the interpretation of the ^{12}CO J=7-6 line observed by other investigators, who suggested that the J=7-6 line is an adequate indicator for the PDR component. To unambiguously detect the hotter gas thought to be a significant component of photodissociation regions, we must re-observe these sources in CO lines with $J \geq 11$. That is what we did in subsequent observations of some Northern Hemisphere clouds in August, 1991 (see following section).

(D) CO 12-11 and CO 14-13 Line Radiation

In August, 1991, we observed the J=12-11 and J=14-13 rotational lines of ^{12}CO in W3, M17, W51, DR 21, and W49. We had previously observed the ^{12}CO J=9-8 line in all these sources and the ^{13}CO J=9-8 line in all but W49. The linewidths of the J=12-11 and J=14-13 lines are typical of those seen in lower-J observations, and identify the emission as emanating from gas which is not likely shock excited, and therefore presumably the photodissociation component [2]. For W51 our J=14-13 and J=12-11 spectra showed similarly narrow lines, about 10 km s^{-1} (FWHM). No evidence was seen for a broad component of 70 km s^{-1} linewidth in W51 IRS 2 or 90 km s^{-1} linewidth in W51 Main, as reported by Jaffe and others in 1987 from Fabry-Perot observations of the J=16-15 transition. The discrepancy is significant, because of the inference of shock activity that broad profiles suggest.

For the 5 sources we observe, the (J=14-13)/(J=12-11) line intensity ratios indicate excitation temperatures ≥ 150 K. The lower limit applies to LTE excitation, which is most likely not the case for high-J CO in these sources. Detailed statistical equilibrium calculations are in progress to define the excitation temperature and density of the gas more accurately. Regardless, the temperatures indicated are consistent with the values of 200-300 K predicted for the PDR component by Tielens & Hollenbach in 1985. It would be very helpful to have additional data on the weaker ^{13}CO lines in order to estimate column densities of hot gas and to pin down the ^{12}CO optical depths. Supporting observations of this type were planned for FY92 so that sufficient constraints would be in place to make a definitive interpretation of the data.

(E) Guest Investigator's Flights

There were four guest investigator flights scheduled in FY91, but only one flown. That flight was in August, 1991 for J. Keene (Caltech) and collaborators, during which the 158 μm fine structure line of ionized carbon was mapped across a number of ionization fronts in selected galactic molecular clouds. Three other GI flights were deferred to FY92 (see below).

II. FY92 Results

In FY92 the spectrometer was flown successfully in three flight series: 3 G.I. flights for J. Keene (Caltech) in October-November 1991, 3 flights in New Zealand in April 1992, and 2 flights from Moffett Field in September 1992. The GI flights for J. Keene were for observations of 158 μm C II primarily in the Orion region. These data were eventually analyzed and published by us [11], and the results are discussed later in this report.

In April 1992 we participated in the Southern Skies Expedition to Christchurch, New Zealand. Our primary goal was to observe the C II line in the Small Magellanic Cloud and selected high density clouds. Unfortunately, no data on the SMC were taken because of telescope system problems. Good data, however, were obtained on all 3 secondary sources: NGC 6334, RCW 57, and Sgr B2.

NGC 6334 and RCW 57 were mapped with dozens of spectra each. Sgr B2 was observed at the (N), (M), and (S) continua peaks, where strong emission was detected at +68 km s^{-1} V_{lsr}, and strong absorption seen from foreground gas at 7 km s^{-1} V_{lsr}. The

absorption component is likely optically thick.

The C II observations of NGC 6334 were analyzed and published [6]. The observations comprised 20 locations spaced at 1 arcmin intervals along a line running NE-SW through the five major peaks of activity (FIR 1 - FIR V). In addition, five positions were observed in a cross-scan though FIR I. The high spectral resolution of the data allows a direct velocity comparison with millimeter wave lines and hydrogen recombination data. There is a general correlation between the C II emission and that of warm dust and CO, as would be expected for phenomena all associated with star formation. Nevertheless, no small scale correlation was found. The C II excitation temperature is higher than that of either dust or CO. The observed lines profiles were complex, with evidence of self-absorption and additional emission from ionized carbon in H II regions. It appears that the photodissociation region, ionized gas region, and colder more tenuous material all contribute to the observed C II emission. Without the high velocity resolution of the heterodyne spectrometer, the respective contributions of these different dynamical components would be difficult to unravel.

The main goal of our Northern Hemisphere observations in FY92 was to detect the 163 μm OH line simultaneously with the J=16-15 line of ^{12}CO and map their intensities along a strip centered at M42/IRc2 between H_2 peak 1 and H_2 peak 2. This was accomplished as proposed during a 2-flight series in September 1992.

As expected, the 163 μm OH emission does not show the pronounced absorption at 5 km s^{-1} V_{lsr} that was seen in the corresponding 119 μm OH line (Betz and Boreiko, Ap. J. Lett., 1989). We want to know whether the spatial distribution of the OH emission matches that of the CO, and hence could be a product of shock-excitation. Our earlier 119 μm results indicated this was not the case. The new data are currently being analyzed with a complex computer code that realistically models the gas excitation under outflow conditions. This is discussed further in the following section that describes FY96-FY98 activities.

In FY92 the ^{12}CO J=16-15 line was also detected in W3, W51, M17, and DR21. In all cases the peak line intensities were $T_r^* = 2$ K to 4 K, and the linewidths were 10-20 km s^{-1}, with M17's being the widest. It is now obvious that most of the high-J CO emission is produced by UV- and not shock-excitation in these sources. This conclusion contradicts earlier interpretations based on the much broader linewidths reported from Fabry-Perot observations on the KAO. Examples of these data with discussion are provided in reference [2].

FY93 and FY94 Results

Although 5 flights were awarded for FY93, none were actually flown. Three flights scheduled for February 1993 were canceled because of aircraft unavailability. These flights were carried over to FY94 and successfully flown in January 1994. Two flights planned for New Zealand in mid-May 1993 were canceled due to illness of the P.I. team. These latter two flights were not carried over to FY94.

A total of 7 flights were scheduled for our spectrometer in January 1994. Five of these were "make-ups" for flights not flown in FY93: 3 for the Betz/Boreiko P.I. group and 1 each for the Tielens/Skinner/Justtanont and the Langer/Frerking G.I. groups. Two

FY94 flights were also flown for the Saykally G.I. group.

Betz and Boreiko observed the J=14-13 lines of ^{12}CO and ^{13}CO at 184 μm and 194 μm, respectively, at a number of positions in the sources W3, M42, and NGC 2024. From the line intensity ratios and the fact that the line profiles are completely resolved at 0.3 km/s resolution, the optical depth of ^{12}CO emission can be deduced for both the quiescent and the shock-excited gas.

The Saykally group searched for the 158 μm Q(4) transition of the C_3 molecule in W3 and M42. Although the expected sensitivities were achieved, no emission or absorption was detected at the line frequency. In a subsequent flight from New Zealand, the R(2) line of C_3 was detected in absorption in Sgr B2. This result was presented at the Airborne Astronomy Symposium [4].

Tielens and Justtanont used our instrument to observe the 289 μm J=9-8 and 184 μm J=12-11 lines of ^{12}CO in a number of late type stars, including IRC+10216. The J=12-11 line was detected in IRC+10216, but the J=9-8 was not, probably because of beam dilution. The data were modeled with a computer code for mass loss from AGB stars, and the results presented at the 1994 Airborne Astronomy Symposium [5] and in a refereed publication [14].

A flight to observe the J=9-8 CO line in galactic molecular clouds for guest investigators Langer and Frerking (JPL) was aborted in February, 1994, because of problems with the telescope door. This flight was rescheduled and flown in March, 1994, from New Zealand. The ^{12}CO J=9-8 line at 1037 GHz was detected from multiple positions in 6 molecular cloud sources: Orion IRc2, Orion bar, OMC 2, OMC 3, Mon R2, and the ρ Oph dark cloud. The data is in the hands of the guest investigators, and we are unaware of its status.

FY95 Results

(A) OI at 63 μm

In 1995 we made a major effort to extend the capabilities of our spectrometer to 63 μm, so that we could observe the ground-state fine structure line of neutral oxygen. Our first priority was the mixer, for which we developed a high-order corner reflector mount [7, 10]. This development was successful, and a fully resolved spectrum of the neutral oxygen line was obtained for Orion M42 in flights from Hawaii in September, 1995 [9]. The 4.7 THz line frequency is the highest yet observed with a Schottky diode heterodyne receiver. By comparing the peak antenna temperature of the O I line with that of C II (also taken with this heterodyne spectrometer), we can constrain the gas kinetic temperature to be 175-220 K, and the gas density to be greater than 2×10^5 cm^{-3} in the observed region. The 6.8 km s^{-1} linewidth (FWHM) for the O I line indicates some broadening due to optical depth effects. The significance of the O I detection lies in the constraints it places on the gas temperature for the photodissociation region. With this temperature and other data from isotopic ionized carbon, we can estimate the $^{12}C/^{13}C$ isotopic ratio for atomic gas.

Data on C II emission from M42 were available from flights taken in 1990 and 1991. The data clearly show emission from ^{13}C II. Before we could estimate the $^{12}C/^{13}C$ isotopic ratio, however, we needed to have a clear understanding of the line center optical depth of the ^{12}C II line. The kinetic temperature data derived from the O I data (see

above) allows us to derive the peak C II optical depth to be about 1.2. From this and the observed $^{12}C/^{13}C$ line intensity ratio, we then get $[^{12}C]/[^{13}C] = 58$, which agrees very well with the value obtained from a relationship between the isotopic ratio and the Galactocentric distance derived from CO measurements [11].

(B) HD at 112 μm

Although H_2 and HD have both been detected at UV wavelengths from the diffuse gas in the foreground of bright stars, and the quadrupole lines of H_2 have been seen in emission at infrared wavelengths from shock- and UV-heated gas, HD has not yet been detected in dense clouds, and only an upper limit for its abundance is available. The D/H ratio is an important cosmological parameter, and its measurement is motive enough for searching for HD. The best lines to look for are the transitions between the lowest rotational levels. Although HD has a weak dipole moment of 8.8×10^{-3} D, the relatively large column density expected in dense clouds should make the line detectable.

In our last flight series in September, 1995, we searched for the J=1 transition of HD at 112 μm toward the Orion nebula. The D/H ratio in regions of star formation is an important parameter for evaluation of models of galactic chemical evolution. While initial examination of our data shows no strong HD emission, more detailed analysis is required to obtain a stringent upper limit to the HD abundance toward IRc2. We anticipate that the data should allow us to reach a fractional abundance of D of better than the interstellar value of 10^{-5}. Detailed modeling of the line profile for both shock and UV excitation conditions will be required to assess the implications of the derived limit to the line integrated intensity.

III. FY96, FY97, and FY98 Results

After September, 1995, we have been continuing the analysis of our KAO data under a no-cost extension, which terminated on Jan. 31, 1998. A number of projects have been completed and published, while other work is partially done but will be completed using other funding.

(A) Far-Infrared Spectroscopy of NGC 3576 (RCW 57)

An analysis of our far-infrared observations of NGC 3576 was published in 1997 [12]. NGC 3576 is one of several components of the RCW 57 H II complex and is a region of active star formation. From analysis of the 158 μm C II data along with that of ^{12}CO J=9-8, J=12-11, and J=17-16 and ^{13}CO J=9-8, we find that the high-J CO emission arises from a spatially compact region near the infrared peak that can be characterized by a kinetic temperature near 150 K and a density $> 5 \times 10^5$ cm^{-3}. The ^{12}CO J=9-8 line is found to be optically thick and arises from a more extended cool region with $T_{kin} = 60$ K. The increase in excitation temperature with rotational level of CO suggests that the ionizing source is located behind much of the molecular cloud. Less than 1 % of the molecular cloud is found in the warm PDR and cloud interface region. The C II fine structure emission is intense over more than a 4′ square and shows a central "self-absorption" feature at many locations. This absorption may be an effect of a cooler or less dense component of ionized gas associated with the foreground molecular cloud.

(B) The Photodissociation Region of NGC 7023

Our collaboration with J. Keene (Caltech) led to a combined publication on carbon observations in NGC 7023 [13]. KAO observations of C II at 158 μm were combined with CSO observations of C I and high-J CO to study the photodissociation region (PDR) associated with the reflection nebula NGC 7023. From limited mapping, the ionized carbon appears to be in part associated with the H I region - inside and at the edges of the ionization cavity around the illuminating star HD 200775. Neutral carbon and ^{13}CO J=3-2 emission are closely associated in the neutral molecular region outside the cavity. Higher excitation CO emission from J=6-5 is seen around the rim interface. The complete data set was compared with predictions from a PDR model calculation. One of the results is that a second PDR region appears to have been created at the surface of the molecular cloud by scattered radiation from HD 200775. This second PDR produces a layer of atomic carbon at the surface of a sheet, which increases the predicted [C]/[CO] abundance ratio 10 %, close to the observed value.

(C) Multitransition Studies of High-J CO

The CO molecule is uniquely suited as a probe of physical conditions in molecular clouds because it is abundant, durable, and has many transitions energetically accessible at temperatures typical of these regions. Since CO has a relatively low permanent dipole moment of 0.1 D, the small critical density for collisional excitation for the lower J levels ($J < 7$) ensures that these levels are usually in LTE, rendering interpretation of intensities relatively straightforward. The microwave transitions of CO (J=1-0 and J=2-1) have been observed for many years with ever smaller beamsizes, and such studies have given valuable information on the physical conditions, spatial distribution, and dynamics of cool material in molecular clouds. Because of the abundance of CO, these lines are almost always optically thick in dense clouds, and thus probe mostly their peripheries. Complementary observations of the equivalent transitions in the less abundant ^{13}C isotopomer then give column densities of cool material through the cloud.

(1) High-J CO in W3, W51, M17, and DR 21

The higher J transitions occurring in the submillimeter and far infrared selectively probe hotter and denser gas. We obtained spectrally resolved profiles of the ^{12}C J=9-8 and ^{13}C J=9-8 transitions in four dense galactic molecular clouds using the KAO. Analysis of these data showed that much of the J=9-8 radiation could be produced from the relatively cool ($T_{ex} = 50$ K) gas that is seen in the lower-J transitions. However, for all the sources observed (W3, W51, M17, DR 21), there was some contribution from a second gas component with either higher density or higher temperature than that producing the J=1-0 line. Unfortunately, the KAO diffraction-limited beam size at the CO jnine frequency is 80" so that this second component was significantly beam-diluted. Therefore, we have extended our CO observations to higher-J, where the beam size is smaller, and the contribution from the cool quiescent gas becomes minimal.

Since the heterodyne spectrometer is fundamentally a rather narrow-band instrument and a large change in operating frequency requires a considerable amount of time, obtaining spectra for several CO transitions requires multiple flights. We have new results for the four sources listed above in the ^{12}C J=12-11, J=14-13, and J=16-15 transitions and, for W3, in the ^{13}C J=14-13 line. Figure 2 of reference [2] (see Appendix 2) shows the ^{12}C spectra obtained at W3 IRS 5. It is immediately obvious that the CO lines

are narrow with FWHM < 10 km/s. This is the case for all four sources, in disagreement with the 70 km/s FWHM derived for the W51 J=16-15 line by Jaffe, Harris, and Genzel (1987). Our data show that the gas is heated through UV radiation and that high velocity shocks do not appear to be present in these regions, contrary to earlier interpretations based on lower resolution observations. The lines are even narrower than those seen in ^{12}C J=1-0 line from the quiescent molecular cloud or in the 158 μm fine-structure line of C II from the PDR with a similar beam size. This shows that the dense, warm part of the molecular material adjacent to the PDR is compact and has a smaller velocity dispersion than the cooler cloud or the PDR. There is a strong dynamical association, however, as shown by the identical V_{lsr} values for the high and low J CO and the C II lines.

Simple comparison of the relative peak intensities in the three transitions shown in Figure 2 gives a lower limit to the kinetic temperature of 200 K. This estimate is obtained under the very unlikely assumption of LTE and equal beam filling for all the observed lines. For the analysis of the CO data up to J=9-8 presented by Boreiko and Betz (1991), a single-component non-LTE large velocity gradient model was developed using levels up to J=17. This model needs to be extended to higher J and, possibly, to two components for the analysis of the present data. Since the ^{12}C J=9-8 line is known to be optically thick, it is likely that the J=12-11 line might also have moderate thickness. Then the decrease in intensity with J could reflect subthermal excitation as well as a decrease in optical depth, and the temperature of the emitting region could be considerably higher than the lower limit given above. In the absence of shock heating, the temperature of this molecular gas cannot exceed that of the PDR, typically calculated to be 300 K in models. Higher temperatures deduced from the CO data would then have immediate significance to parameters, such as photoelectronic heating efficiency, important to PDR models.

(2) High J CO in M42

The structure and physical conditions of the IRc2 region of Orion have been significantly affected by mass outflow and shocks. Spectra taken toward IRc2 show several coexisting components: a ridge of quiescent molecular gas, an H II region with an associated PDR, a compact "hot core" with high density and moderate temperature, a low-velocity 18 km/s outflow, and high-velocity shock-excited gas. All five of these are characterized by different densities, temperatures, and dynamical conditions, and a proper understanding of the IRc2 region requires that these be treated individually. Such a task is clearly impossible with integrated intensity measurements obtained with moderate beamsizes. The beam of the KAO in the far infrared is 30" at 100 μm, which is too large to isolate the hot core or to delineate the other components spatially. That feat will only be possible with a larger telescope such as SOFIA, or interferometrically. However, different gas components can be distinguished by their Doppler velocity characteristics. The outflows produce much broader emission than any of the other gas components, while the V_{lsr} centroids for the hot core and PDR emission are quite different (5.0 km/s versus 8.5 km/s). The quiescent molecular ridge gas cannot be distinguished from the ionized and PDR material spectrally, but the different excitation conditions extant in the two regions allow reasonable estimates for the source of observed narrow emission to be made.

Our previous KAO observations of the J=22-21 line of CO toward IRc2 showed that the emission arises in gas with $T_{kin} = 600$ K. Two components could be clearly distinguished, with the wider one most likely produced by swept-up material behind a shock front, and the narrow one originating in a thin layer at the leading edge of the shock. In order to relate this high-temperature emission to the quiescent gas seen in low-J CO data, we have observed a range of transitions from ^{12}CO J=9-8 to J=16-15 and ^{13}CO J=9-8 to J=14-13 . As discussed previously for W3 and the other ''summer'' sources, the J=9-8 emission is largely attributable to the same molecular material as is traced in the J=2-1 and J=1-0 CO lines. From comparisons of our J=14-13 ^{12}CO and ^{13}CO data from IRc2, we can calculate the optical depth in the ^{12}CO line and estimate the excitation temperature and minimum density in the emitting region. It is clear, however, that there is a significant thermal gradient within the region, especially in the vicinity of the shock front, and that a single density and temperature model is completely inadequate. Analysis of the line profiles over the range of transitions which we have observed should give a better measurement of the density, since subthermal excitation becomes increasingly important at higher J. In addition, we will be able to construct a more detailed model incorporating realistic thermal gradients, given the constraints imposed by all the observed profiles. The high signal to noise ratio of the spectra should also permit us to deduce an association between dynamic and thermal properties of the various gas components, and perhaps to better constrain our knowledge of the characteristics of the shock in this region of Orion.

We have also done limited mapping of the Orion PDR in the ^{12}CO J=9-8 line. This transition was chosen because it has low enough excitation to be observable in the quiescent molecular cloud, but also is sensitive to hotter material such as that in the shocked gas. The dramatic changes in observed lineshapes between IRc2 and the bar region 3′ away reflects the different heating mechanisms prominent in the two locations. At IRc2, a shock plays a major role in the dynamics of the gas, whereas the bar is a UV-heated PDR and no outflows are present. Once we have used the information contained in the line profiles at IRc2 to isolate the spectral signatures and relative contributions of several gas components, we will be able to utilize the spatial information to trace the physical extent of these components and to improve our understanding of the interactions between them. Preliminary analysis of the maps suggests that most of the warm material in the Orion region is quiescent and associated with PDRs rather than with shocks. Although our mapping is more limited than that available at higher frequencies with incoherent spectrometers, the information contained is unique in that we can distinguish the relative importance of different dynamical regimes. This is impossible if only integrated intensity maps are available.

(3) OH in M42

Emission from the far infrared rotational lines of OH near IRc2 has generally been interpreted as coming from shock-excited material. Hydromagnetic shock models predict an OH abundance enhancement of about a factor of 25 in the postshock material relative to the cooler gas downstream. This increased abundance along with the high density and temperature in the shocked region suggests that strong OH emission should be present. Both the intensities and profiles of the OH lines reflect physical conditions, such as the density, temperature, and dynamics, within the emitting region.

Several transitions in both the $^2\Pi_{1/2}$ and $^2\Pi_{3/2}$ ladders of ^{16}OH have previously been observed with velocity resolution up to 24 km/s. This resolution was sufficient to obtain an approximate measurement of the width of the broad shock-excited component but not to determine the detailed line profile. Comparison of the relative intensities of various transitions suggested that the ground state 119 µm transition was too weak relative to the other lines measured for a single-component model to be valid. Even with several gas components in the model, the calculated profile and central V_{lsr} of this line were not in good agreement with the data. Our subsequent heterodyne measurements with 0.6 km/s resolution showed the presence of strong absorption in the blueshifted half of the 119 µm line, probably caused by OH in the expanding postshock gas which has density too low to populate the upper state of the observed transition. This absorption provides a simple explanation for the apparently low integrated intensity in this line relative to that in other OH transitions.

We have recently observed the 163 µm transition of OH (which terminates at the lowest rotational level of the $^2\Pi_{1/2}$ ladder) at high spectral resolution. The profile of this line might be expected to show absorption similar to that seen in the 119 µm transition, depending upon the strength of the "cross-ladder" interactions. We were able to observe the 163 µm line of OH simultaneously with the ^{12}CO J=16-15 line in opposite sidebands of the spectrometer. The CO and OH emission profiles are very similar. This is significant in that our multitransition study of CO shows that this radiation arises from several physical components of the gas, not just primarily from the shocked region. Therefore the OH also is not confined to the shocked and post-shocked gas. The very different line shapes of the 119 µm and 163 µm transitions will require detailed modeling to reproduce, and should give considerable insight into the physical conditions of the OH-emitting and absorbing regions. We were also able to make a limited map simultaneously in the 163 µm CO and OH lines. Comparison of the spatial distribution of the CO and OH, with no differential pointing uncertainty, will give more information on the relative importance of the shocked gas in producing or enhancing OH emission.

We are currently analyzing all the OH data with a new radiation transfer code for an expanding spherically symmetric source. This geometry, which is appropriate for the Orion outflow source responsible for much of the shock-excited gas in this region, should give us more realistic modeling of the OH line profiles. A manuscript detailing our conclusions should be available by the end of calendar 1998.

As a final comment, we wish to express our gratitude to the NASA Ames based staff of the Kuiper Airborne Observatory, whose efforts, often beyond the call of duty, ensured that this facility was always at the forefront of infrared astronomy. The success of the flight program described above is to a large extent the result of their efforts. As NASA moves on to SOFIA, we can only hope that the new staff and crew will be able to maintain the fine tradition of the KAO.

Publications from NAG2-753

1. Boreiko, R. T., and Betz, A. L. 1993, "A search for the rotational transitions of H_2D^+ at 1370 GHz and H_3O^+ at 985 GHz", ApJ, 405, L39-L42

2. Betz, A. L., and Boreiko, R. T. 1995, "FIR line profiles as probes of warm gas dynamics", in ASP Conf. Series, Vol. 73, *Airborne Astronomy Symposium on the Galactic Ecosystem: From Gas to Stars to Dust,* ed. M. R. Haas, J. A. Davidson, and E. F. Erickson, (San Francisco: ASP), 41-44

3. Boreiko, R. T., and Betz, A. L. 1995, "Far-infrared heterodyne spectrometer", in ASP Conf. Series, Vol. 73, *Airborne Astronomy Symposium on the Galactic Ecosystem: From Gas to Stars to Dust,* ed. M. R. Haas, J. A. Davidson, and E. F. Erickson, (San Francisco: ASP), 587-588

4. Van Orden, A., Cruzan, J. D., Provencal, R. A., Giesen, T. F., Saykally, R. J., Boreiko, R. T., and Betz, A. L. 1995, "A search for the C_3 carbon cluster in the interstellar medium", in ASP Conf. Series, Vol. 73, *Airborne Astronomy Symposium on the Galactic Ecosystem: From Gas to Stars to Dust,* ed. M. R. Haas, J. A. Davidson, and E. F. Erickson, (San Francisco: ASP), 67-70

5. Skinner, C. J., Justtanont, K., Tielens, A. G. G. M., Betz, A. L., and Boreiko, R. T. 1995, "Physical structure of the IRC+10216 wind: molecular sidereoarchaeology", in ASP Conf. Series, Vol. 73, *Airborne Astronomy Symposium on the Galactic Ecosystem: From Gas to Stars to Dust,* ed. M. R. Haas, J. A. Davidson, and E. F. Erickson, (San Francisco: ASP), 433-436

6. Boreiko, R. T., and Betz, A. L. 1995, "Ionized carbon in NGC 6334", ApJ, 454, 307-315

7. Betz, A. L., and Boreiko, R. T. 1995, "A practical Schottky mixer for 5 THz", in *Proc. Sixth International Symposium on Space Terahertz Technology,* (Pasadena, CA, March 21-23 1995), 28-33

8. Jansen, D. J., Van Dishoeck, E. F., Keene, J., Boreiko, R. T., and Betz, A. L. 1996, "Physical and chemical structure of the IC63 nebula. III. Gas-phase carbon abundance", A&A, 309, 899-906; A&A, 315, 327

9. Boreiko, R. T., and Betz, A. L. 1996, "Heterodyne spectroscopy of the 63 μm O I line in M42", ApJ, 464, L83-L86

10. Betz, A. L., and Boreiko, R. T. 1996, "A practical Schottky mixer for 5 THz (part II)", in *Proc. Seventh International Symposium on Space Terahertz Technology,* (Charlottesville, VA, March 12-14 1996), 503-510

11. Boreiko, R. T., and Betz, A. L. 1996, "The $^{12}C/^{13}C$ isotopic ratio in photodissociated gas in M42", ApJ, 467, L113-L116

12. Boreiko, R. T., and Betz, A. L. 1997, "Far infrared spectroscopy of C II and high J CO emission from warm molecular gas in NGC 3576", ApJS, 111, 409-417

13. Gerin, M., Phillips, T. G., Keene, J., Betz, A. L., and Boreiko, R. T. 1998, "CO, C I and C II observations of NGC 7023", ApJ, 500, 329-341

14. Skinner, C. J., Justtanont, K., Tielens, A. G. G. M., Betz, A. L., Boreiko, R. T., and Baas, F. 1998, "Modelling the dust and gas outflows from IRC+10 216 I: Ground-based and airborne observations", MNRAS(in press)